CARBON MITIGATION POTENTIAL AND COSTS OF FORESTRY OPTIONS IN BRAZIL, CHINA, INDIA, INDONESIA, MEXICO, THE PHILIPPINES AND TANZANIA

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Abstract. This paper summarizes studies of carbon (C) mitigation potential[1] and costs of about 40 forestry options in seven developing countries. Each study uses the same methodological approach – Comprehensive Mitigation Assessment Process (COMAP) – to estimate the above parameters between 2000 and 2030. The approach requires the projection of baseline and mitigation land-use scenarios. Coupled with data on a per ha basis on C sequestration or avoidance, and costs and benefits, it allows the estimation of monetary benefit per Mg C, and the total costs and carbon potential. The results show that about half (3.0 Pg C) the cumulative mitigation potential of 6.2 Petagram (Pg) C between 2000 and 2030 in the seven countries (about 200×10^6 Mg C yr^{-1}) could be achieved at a negative cost and the remainder at costs ranging up to \$100 Mg C^{-1}. About 5 Pg C could be achieved, at a cost less than \$20 per Mg C. Negative cost potential indicates that non-carbon revenue is sufficient to offset direct costs of these options. The achievable potential is likely to be smaller, however, due to market, institutional, and sociocultural barriers that can delay or prevent the implementation of the analyzed options.

Keywords: barriers, Brazil, carbon (C), China, climate change mitigation potential, costs, forestry, forest protection, forestation, India, Indonesia, Mexico, the Philippines, Tanzania

1. Introduction

Forests play an essential role in the global carbon (C) cycle.[2] Tree growth in forests serves as an important means to capture and store atmospheric CO_2 in vegetation, soils and forest products. Terrestrial ecosystems provide temporary storage for carbon since it may be released by anthropogenic and natural disturbances, and forest products and litter can decay over a finite period of time. The temporal feature of C

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storage in forests implies that its primary role will be to sequester carbon for finite time periods, which will allow the implementation of more permanent options for the avoidance of greenhouse gas (GHG) emissions, and stabilization of climate change. The substitution of products from sustainably managed forests for carbon-intensive and other forest products, or for carbon-intensive fuels, however, offers an opportunity for the permanent removal of GHG emissions.

The 2000 IPCC Second Assessment Report (SAR) noted that the technical potential for carbon sequestration through forestry activities ranged from 55–76 Pg C for the period 1995 to 2050 (Brown et al. 1996). A more recent assessment of the technical potential of land use, land-use change and forestry (LULUCF) options suggests that the total global potential for afforestation and reforestation activities between 1995 and 2050 will average between 1.1–1.6 Pg C per year, of which 70 percent will be in tropical forests (Schlamadinger and Karjalainen et al. 2000). An assessment of potential sequestration from improved land use management and other land-use changes suggests that by 2010, the additional potential may exceed 1.3 Pg C yr^{-1}, rising to about 2.5 Pg C yr^{-1} by 2040 (Sampson and Scholes et al. 2000). The LULUCF technical potential estimated by Sampson and Scholes et al. (2000), represents about one sixth of the average annual CO_2 emissions from fossil fuel combustion and cement production estimated to be 6.3 ± 0.6 Pg C per year from 1989 to 1998 (Watson et al. 2000).

The achievable potential from LULUCF options, taking into consideration the economic, social, and institutional barriers to reaching the technical potential, however, is some unknown fraction of this estimate. Achieving such a potential may require domestic programs and policies, and international agreements in order to accelerate the market penetration of the options. The experience with the Tropical Forestry Action Plan initiative in the late 1980s suggests that even globally agreed, well-funded, nationally supported efforts can fail (Winterbottom 1990).

The C sequestration potential noted in the SAR amounts to between 8.7 to 12.1 years worth of aforementioned average annual CO_2 emissions from fossil fuel combustion and cement production. Part of the total SAR forestry potential, namely 40–61 Pg C, is estimated to lie in the low-latitude countries, and about 1.7 Pg C in China. If this potential could be fully tapped, a formidable challenge, forestry mitigation activities in these countries could delay the increase in global atmospheric C emissions by 6.4 to 9.7 years. Hence, forestry mitigation options can help, but reduction of fossil fuel emissions and/or other technological pathways for C sequestration will be essential for climate change stabilization.

The forestry potential varies across countries depending on the suitability of their land for forestation, the levels of current and future CO_2-emitting activities, potential for substitution in C-intensive services and products, and of other options for reducing deforestation. The Republic of Korea for example is estimated to have a mitigation potential twice its 1990 fossil fuel C emissions, while the Philippines is estimated to have a 200-fold potential (ALGAS 1998). The amount of time it takes to tap this potential depends on the mix of forestry mitigation options that is suited to each country. Reducing deforestation potentially could be achieved over a short time span if appropriate socioeconomic incentives were established and maintained to halt activities that cause deforestation and the misuse of forest resources. Forestation would take longer simply because tree growth generally requires between 10 and 70 years, varying by species, soil conditions, precipitation, solar insolation levels, and the silvicultural regime employed.

A number of scientific and policy questions are being asked in international and national debates by three sets of actors – national governments and negotiators, potential investors in GHG mitigation offsets, and local communities and other stakeholders. Which forestry mitigation options are the most important for developing countries and local communities? How much additional C stock might be created, and how much emissions reduction might be achieved through these mitigation activities? What is the cost per ton of carbon and the total cost of these options?

The set of papers in this volume addresses these and related questions under the auspices of the F7 Tropical Forestry Climate Change Research Network coordinated by the Lawrence Berkeley National Laboratory (LBNL) and US Environmental Protection Agency (EPA). Using the same computational model, Comprehensive Mitigation Assessment Process (COMAP) (Sathaye et al. 1995), the authors have analyzed these questions for Brazil (Fearnside 2001), China (Xu et al. 2001), India (Ravindranath et al. 2001), Indonesia (Boer 2001), Mexico (Masera et al. 2001), the Philippines (Lasco and Pulhin 2001) and Tanzania (Makundi 2001).

The COMAP approach requires the projection of land-use scenarios for a baseline case, and for multiple mitigation cases. In parallel, it requires baseline and mitigation option data on a per ha basis on C sequestration or avoidance, and costs and benefits, in order to estimate the net monetary benefit per ha or per Mg C. These estimates are then combined with the land use scenarios in order to estimate cumulative or annual C flows and monetary costs and benefits over a future period.

This paper provides a summary evaluation of the results from the studies of seven countries. It illustrates the potential and costs of options across countries, and provides some observations on how the analysis of mitigation potential and costs of forestry mitigation options could be improved to provide more realistic estimates of both. The studies focus on quantifying the benefits of forestry practices, and generally do not identify policy changes or incentives necessary for their implementation. The potential barriers to implementation, and monitoring of C stock, raise complex issues with institutional, socioeconomic, public policy, gender role, and economic ramifications that would need to be addressed in order for these technically feasible options to be realized successfully, and sustained in the field.

TABLE I

Summary of mitigation options in seven countries

Study country	Options included in the study	
Brazil	Afforestation (Short- and long-rotation)	
China	Afforestation (Short- and long rotation), Agroforestry, Regeneration	Bioenergy
India	Afforestation (Short- and long rotation), Regeneration	Forest protection
Indonesia	Forest plantation and timber estate, Afforestation, Reforestation, Enhanced natural regeneration	Forest protection, Bioelectricity, Reduced impact logging
Philippines	Afforestation (short and long rotation), Natural regeneration,	Forest protection, Bioenergy
Mexico	Long- and short-rotation plantations, Forest restoration, Agroforestry	Sustainable forest management, Bioenergy
Tanzania	Community short rotation plantations, Long rotation softwood plantations	Long rotation hardwood plantations

Note: The options listed in this table are reported in the papers for each country in this volume. For Brazil, the two options are based on land use change scenarios from Trexler and Haugen (1995), and cost and benefits data and information from Fearnside (1995) and Meyers et al. (2000).

2. Potential Mitigation Activities and Features

Forestry mitigation activities may be grouped into three categories (Brown et al. 1996, 2000). The first category includes activities that avoid the release of emissions from C stock, such as forest conservation and protection. The second includes activities that store C, for example afforestation, reforestation and agroforestry, and the third category involves substituting the use of C-intensive products and fuels with sustainably harvested wood products and wood fuel, for example wood substituting for concrete or steel and bioelectricity substituting for fossil fuel electricity.

The selection of the options to assess was made by the authors for each country, and reflects major opportunities under debate or in programmatic form already. The extent and magnitude of activities differs across countries. The analysis of activities that avoid the release of C emissions was done for India, Indonesia, and the Philippines (Table I). Slowing or stopping deforestation may be the fastest way to reduce C emissions – although arguably the most difficult to establish and maintain. The causes of deforestation vary across study countries and change over time. In Brazil deforestation is mainly due to conversion to pasture and agricul-

TABLE II

Characteristics of typical mitigation options across studies in seven countries

Option	Initial cost ($\$$ ha^{-1})	Rotation period (yr)	Mean annual increment (Mg ha^{-1} yr^{-1})
Short-rotation	150–450	7–8	3.8–19.2
Long-rotation	450–700	25–40	1.6–11.1
Regeneration/management	18–40	40–80	0.8–3
Protection/conservation	5–10*	NA	NA

Notes: Figures show ranges of estimates from the studies. Significant variations from these values are discussed in the text. Within each category of option, studies have evaluated more specific mitigation activities.

* Exclude opportunity costs of land, which vary substantially and are accounted for in the estimates for each study country.

NA – not applicable.

ture, in Mexico conversion and fuel wood extraction are the main causes, while in Indonesia and the Philippines, deforestation is mostly caused by conversion of forests to agriculture (e.g., transmigration and shifting cultivation), and forest fires. In India, forest loss is due mainly to wood extraction, while in Tanzania, more than 80 percent of deforestation is due to conversion to agriculture and woodfuel extraction (Makundi and OKiting'ati 1999).

Improved management of natural forests could play an important role in slowing deforestation in Mexico and the Philippines. Community woodlot programs and options for improved efficient kilns and wood stoves can significantly reduce deforestation in Tanzania. Also, intensive agricultural practices and agroforestry have a high potential for reducing the deforestation caused by shifting cultivation. Reduced impact logging (RIL) has potential in Indonesia. A well-known RIL project is being implemented in Malaysia (Pinard and Putz 1997) and the Indonesia study evaluates the economic implications of similar activities in that country.

The studies evaluate the potential for forestation activities in each study country. The types of forestation activities vary from short- and long-rotation plantations to agroforestry, and natural, and enhanced natural regeneration. Agroforestry is evaluated in the study for China and Mexico. For India and Indonesia, a sustainable forestation program is envisioned that could supply the future demand for industrial wood products and other biomass needs of the country. In Indonesia, the forestation activities would be carried out on plantations, and timber estates, and through social forestry and transmigration programs of resettlement to less-densely-populated islands. The potential for bioenergy is evaluated in the studies for China, Indonesia, the Philippines, and Mexico.

2.1. Characteristics of Mitigation Options

Mitigation analysis requires a characterization of the options to be evaluated. The characterization typically includes information on the C stored in various pools, its biomass growth and decay rates, the fate of the biomass, and the option's costs and benefits. Table II shows the range of values for the primary options across study countries. The ranges exclude outliers that are caused by unusual circumstances in the country, e.g., the very low exchange rate in Indonesia triggered by the Asian financial crisis in 1997–98 made costs in US dollars about half or less than those prior to this period.

The mean annual increment refers to the average rate of biomass growth over the life of a forestation option. For regeneration options, it varies from as low as 0.8 Mg C ha^{-1} yr^{-1} in China to about 3 Mg C ha^{-1} yr^{-1} in the Philippines, and for long-rotation plantations from 1.6 Mg C ha^{-1} yr^{-1} in China to as high as 11.1 Mg C ha^{-1} yr^{-1} in Tanzania. The short-rotation plantations have higher rates ranging from 3.8 Mg C ha^{-1} yr^{-1} in China to 19.2 Mg C ha^{-1} yr^{-1} in Tanzania. To the extent data permitted, each study accounted for the increase in soil carbon, which was estimated to range from 0.5 Mg C ha^{-1} yr^{-1} in China to 3 Mg C ha^{-1} yr^{-1} in India.

Among the various forestation options listed in Table I, the rotation period varies from as short as 7–8 years for short-rotation planting in Mexico and India to as much as 50 years in the case of restoration plantations in Mexico. Generally the long-rotation plantations have periods ranging between 25–40 years. Regeneration options in each country have much longer periods to maturity, lasting as high as 80 years in northeastern China.

The cost of planting is relatively uniform and stable over time and reflects the overall income levels in the country. Costs tend to be higher in Mexico (about \$400–500 ha^{-1}), and lower in India, the Philippines, China and Tanzania (between \$150–300 ha^{-1}). Costs tend to be higher for long-rotation plantations. The life-cycle costs of these options, excluding harvesting, are only somewhat higher since the annual recurring cost of plantations tend to be small relative to the initial cost. The recurring costs include the cost of monitoring of C stocks.

In Indonesia, because of the three- to four-fold drop in the value of the Indonesian currency (the Rupiah) since 1997, current costs in US dollars are significantly lower. Initial establishment costs range between \$18 ha^{-1} for enhanced natural regeneration to about \$50 ha^{-1} for a short-rotation plantation. However, once the devaluation effects run through the monetary, factor and product markets, the long-term cost structure may well return.[4]

The costs of forest protection/conservation (excluding opportunity costs) and management options tend to be lower than those for forestation. Forest protection costs range from as low as \$5 ha^{-1} in the Philippines based on government budgets to higher values in the other countries. Experience in the countries shows that the lower values are clearly inadequate to accomplish conservation goals, and after

TABLE III

Historical forest and land-use patterns in seven countries

Country	Total land area (× 10^3 ha)	Forested area (× 10^3 ha)	Deforestation rate in study area (× 10^3 ha yr^{-1})	Land suitable for forestation this study (× 10^3 ha)	Land suitable for forestation A 1995 study[p] (× 10^3 ha)
Brazil	845,700	390,000[n]	1113–2906[m]	85,000[l]	85,000
China[a]	963,296	115,600[k]	60	31,953[d]	
India	328,760	63,300[b]	274[c]	53,200	35,000
Indonesia[f]	192,401	104,500	750–1,500	31,000[e]	13,600
Mexico	196,700	115,652	720[I]	21,000[j]	35,500
Philippines	30,000	5,200	99[h]	4,400[g]	8,000
Tanzania	89,161	41,857	750	7,500[o]	11,100
Total	2,556,857	837,593	Not Applicable	234,053	188,200

* Source = FAO Forest Resource Assessment 2000, with –ve figure implying threshold. [a] – 20% crown cover. Data are for 1998. [b] – Data for 1995; [c] – Data for 1995–97; [d] – Degraded lands in three study regions in 2000; [e] – Unproductive land, grasslands and critical lands; [f] – Annual average for 1990–1997 (includes transmigration and agricultural development, forest fire and shifting cultivation; excludes illegal logging). [g] – Grassland areas, sub-marginal forests and brushlands; [h] – Annual average for 1995–1998 period; [i] – Early 1990s. Forest area includes semi-arid vegetation, which accounts for 66 $\times 10^6$ ha; [j] – Degraded forest land; [k] – Forested area in three study regions. Total forested area is 158,941 thousand ha; [l] – Estimated potential for natural regeneration, farm forestry and plantations from Trexler and Haugen (1995); [m] – 1978 to 1997 data from Brazil web site (www.mct.br/clima/ingles/communic_old/amazinpe.htm); [n] – Forests and 'cerrados' located in the Amazon region only. [o] – 3.5 × 10^6 ha for short rotation community woodlots, and 2.5 × 10^6 ha (50% of the fallow area) for reforestation and 1.5 × 10^6 ha for all other forestation including agro-forestry, long rotation plantations, non-forest tree crops (wattle, rubber, oil palm, etc); [p] – Figures from Trexler and Haugen (1995). Estimated potential in regeneration, farm forestry and plantations between 1990 and 2040.

factoring in the opportunity cost of land and labor, costs in every study country exceed the monetary benefits of forest protection/conservation.

3. Land-use: Historical Trends and Future Scenarios

3.1. Historical Land-use Patterns

The study countries constitute a very large land area of the world. Individually, the land area ranges from over 963 $\times 10^6$ ha for China, closely followed by Brazil's 845 $\times 10^6$ ha, to 30 $\times 10^6$ ha for the Philippines (Table III). The forested area varies considerably, with Indonesia having as high as 57% of the land area in forests, followed by Brazil and Tanzania with 46% each. China has the lowest proportion (11%) of the land area under forest cover. The India, Indonesia, Mexico, and Philippines studies focus on the entire forested area in each country, while the Brazil study focuses on the Amazon region, and the China study on the three most forested regions out of five in the country, the northeast, southeast and southwest. The Tanzania study focuses on the miombo woodlands, which constitute about 95% of the forested area in the country and accounted for about 90% of the annual deforestation (Makundi and OKiting'ati 2000).

The rate of deforestation is a highly complex and contested figure in any country, and thus difficult to compare across countries. The magnitude of deforestation is substantial even in countries where forest resources are not abundant. The rate of deforestation for Indonesia has been reported to range from 0.75 to 1.5 $\times 10^6$ ha yr^{-1} in the 1995–97 period (Table III) (MOF 1996; Walton and Holmes 2000). The rate for Brazil has fluctuated from 1.1 to 2.9 $\times 10^6$ ha from the late 1980s to early 1990s (www.mct.br/clima/ingles/communic_old/amazinpe.htm). The estimates of deforestation for Tanzania and Mexico are about 0.750 and 0.720 $\times 10^6$ ha per year respectively, though the official figures claim a lower rate in both countries (Makundi and OKiting'ati 2000 op. cit.; Masera et al. 1997). Slowing deforestation would clearly reduce emissions but implementing options and enforcing policies to achieve this is often thwarted by the high opportunity cost of land and labor.

Is there enough land available for climate mitigation activities in the developing countries? At first glance, the prohibitively high population densities and low agricultural productivity in some of the study countries might seem too restrictive to allow land to be used for forestation. As Table III indicates, however, the degraded or wasteland estimated to be available for forestation, without considering economic, social, cultural, and other barriers, amounts to several tens of millions of hectares. For comparison, Table III also shows the potential estimated by Trexler and Haugen (1994) for regeneration, farm forestry and plantations options for the period 1990 to 2040. This land either originally contained forests or has been left fallow and agriculture is no longer practiced for various social and economic reasons. Much of this land is suitable or could be made suitable for forestation programs in the study countries. This may require a change of management from individual farmers to that by private companies and commensurate harvesting, or include incentives to individual farmers to re-orient their land use practices. China and India both import wood products with a value of several hundreds of millions of dollars (Kadekodi and Ravindranath 1997; Zhang et al. 2000), and forestation programs on such lands could offset at least part of this drain on their foreign exchange reserves, while simultaneously providing rural socioeconomic benefits if the programs were sustainably managed.

3.2. Future Land-Use Scenarios

A baseline scenario, and one or two alternative mitigation scenarios were constructed for each study country for the period 2000–2030. The baseline scenario represents a set of assumptions about likely changes in land-use and land-cover

TABLE IV

Land area scenarios in seven countries ($\times 10^6$ ha)

Country	2000–2012	2000–2030	Mitigation scenario description
Brazil			Based on Trexler and Haugen 1995
Forestation	6.8	19.8	
China			Technical plan scenario – portion of the government
Forestation	7.6	19.7	plan is achieved in each of the three regions
Forest Protection	5.1	13.5	
India			Sustainable forestry scenario that is designed to
Forestation	12.2	29.5	meet biomass demand through domestic
Forest protection	3.6	8.5	LULUCF activities.
Indonesia			As above for India.
Forestation	11.6	29.2	
Forest protection	0.5	1.1	
Philippines			Scenario assumes 50% of the rate of land
Forestation	0.6	1.7	development under the government plan
Forest protection	0.07	0.13	
Mexico			More effective and wider implementation of
Forestation	3.0	9.1	baseline scenario activities to meet domestic
			biomass demand.
Tanzania			Meets 50% of demand for woodfuel, sawlogs and
Forestation	0.4	1.7	chiplogs, by 2024.
Total			
Forestation	42.2	110.8	
Forest protection	9.2	23.2	

patterns in the country based on historical data and emerging demographic and economic trends. In the mitigation scenarios, activities such as afforestation or forest protection are explicitly identified, and simulated using the COMAP model in order to estimate the change in the number of hectares and associated carbon stock for each type of land use throughout the period under consideration, as well as costs and selected benefits. Several study countries have ambitious government plans that have been only partially implemented because of lack of resources, economic and policy incentives, and social reasons. The studies analyzed the forestry sector targets set forth in these government plans to gage their resource needs. Table IV shows the land-use scenarios that form the basis for the mitigation scenarios presented in this summary paper. Additional mitigation scenarios analyzed for each country are presented in the study country papers. The forestation land scenario values in Table IV may be compared with the land suitable for forestation values in Table III. The scenarios are described below:

Brazil: One mitigation scenario was analyzed in a preliminary analysis using the COMAP model. This limited scenario is based on land use projections from Trexler and Haugen (1995), for regeneration and plantation activities only; other options like avoided deforestation or forest management are not included since corresponding cost data were not readily available to the authors. The baseline scenario assumes that future land would have remained in its current state. We focus on two selected activities among many others that could be implemented. The total land area under mitigation amounts to 19.8 $\times 10^6$ ha by 2030.

China: Two alternative scenarios were analyzed. One scenario reflects government plans which call for forest area to be increased by 27.3 $\times 10^6$ ha from 1999 to 2010 and by another 46 $\times 10^6$ ha from 2011 to 2030, and 18.9 $\times 10^6$ ha and 35 $\times$ 10^6 ha of new nature reserves would be established during the respective periods. In addition, China plans to establish 13 $\times 10^6$ ha under agroforestry between 1999 to 2010. Table IV shows a second more conservative scenario that would achieve a percentage of the goals of the government plan. The land available for regeneration is an order of magnitude higher than that for short- and long-rotation plantations by 2030.

India: Two alternatives, a sustainable forestry scenario, which is shown in Table IV, and a commercial forestry scenario were evaluated. The first one is designed to meet the incremental national biomass demand between 2000 and 2030, and includes increased forest protection and regeneration options. The second one focuses on meeting the increased biomass demand primarily through commercial forestry. The wasteland available for forestation is quite large, almost 30 $\times 10^6$ ha, and the amount of land that could benefit from additional protection is 8.5 $\times 10^6$ ha.

Indonesia: Two alternative scenarios, a government-plans scenario and a mitigation scenario, were analyzed. The first scenario projects forestation rates similar to those in the government plan as laid out in Repelita VI (1998–2003), although historically these have been rarely achieved. The mitigation scenario assumes that the rate of timber plantation establishment is increased such as to meet all future wood demand (Table IV). Short-rotation plantations, enhanced natural regeneration, long-rotation reforestation, and reduced impact logging options dominate the 29.2 $\times 10^6$ ha of land available for forestation activities.

Philippines: As in the case of Indonesia, the government's forestry master plan scenario and a mitigation scenario are analyzed. The master plan assumes aggressive tree planting to meet local demand for wood products. The second scenario assumes a forestation rate, which is 50% of the government plan scenario (Table IV). The total land area available for mitigation in this scenario is relatively small, about 1.7 $\times 10^6$ ha by 2030; much of this is concentrated in short- and long-rotation plantations. Another 0.1 $\times 10^6$ ha is identified for protection.

Mexico: One alternative mitigation scenario is analyzed, which assumes improved penetration of all mitigation activities. In this scenario, 2030 deforestation rates are reduced to 25% of current ones, native forests are managed more efficiently with improved survival rates, plantations make Mexico self-sufficient in paper and cellulose products, and bioenergy plantations play a prominent role (Table IV). Restoration plantations, i.e., plantations established to restore degraded land, and management of temperate forests constitutes the bulk of the land requirements for mitigation activities. By 2030, a total area of 9.1×10^6 ha would be under some form of mitigation activity in this scenario.

Tanzania: The main mitigation scenario analyzed involves implementation of the Tropical Forest Action Plan (TFAP) for establishing community short rotation plantations to meet 50% of the demand for wood fuel, sawlogs and chiplogs. The scenario analyzed involves the conversion of 1.7×10^6 ha of woodlands to short rotation plantations terminating in 2024, assuming that the demand for these products will have peaked, and the plantations are managed in perpetual rotations (Table IV). Other less extensive afforestation scenarios for long rotation industrial softwood and hardwood plantations were analyzed. The TFAP conservation program, which has largely remained unimplemented, since proposed in 1989, was also analyzed.

3.3. CARBON STOCK SCENARIOS[5]

The live vegetation C stock in the study regions varies with the largest stock in Brazil, followed by Mexico, Indonesia, China, India, Tanzania, and the Philippines. The land-use and land-cover change scenarios lead to significant opportunities for improving the biomass and C pools in the future, which increase with the time period of study. By 2030, the alternative scenarios capture significantly more carbon than say by 2012, the last year of the commitment period stipulated in the UNFCCC Kyoto Protocol.

Table V shows the changes in the live vegetation C stock in the baseline mitigation scenarios for several study countries. Except in China, the total C stock declines in the other countries between 1990 and 2030 in the baseline scenario because deforestation is anticipated to continue in the future. Slowing deforestation thus constitutes an important opportunity to reduce or avoid emissions. These figures indicate the potential for incremental or additional C storage in the study countries. By 2012, the difference in carbon stock varies between 53×10^6 Mg C in Tanzania to 728×10^6 Mg C in Indonesia. The cumulative potential by 2012 compared to 2000 amounts to 1851×10^6 Mg C.

The options contributing to this mitigation potential vary across the study countries. In China, regeneration contributes by far the largest amount to the mitigation potential, in India, the potential is highest for forest protection followed by long- and short-rotation forestry; in Indonesia, forest protection, long-rotation plantations, and short-rotation reforestation are the primary contributors to mitigation, in the Philippines, short and long-rotation plantations, and forest conservation are

TABLE V

Carbon stock in mitigation and baseline scenarios for seven countries ($\times 10^6$ Mg C)

Country	2000	2012	2030
Brazil:			
Baseline scenario	Not available	Not available	Not available
Mitigation scenario	Not available	Not available	Not available
Increment	0	87	448
China:			
Baseline scenario	11115	11197	11321
Mitigation scenario	11115	11236	11532
Increment	0	39	261
India:			
Baseline scenario	5731	5727	5720
Mitigation scenario	5731	6053	6680
Increment	0	326	960
Indonesia:			
Baseline scenario	17450	16500	16140
Mitigation scenario	17450	17228	18650
Increment	0	728	2540
Philippines:			
Baseline scenario	1130	965	805
Mitigation scenario	1130	990	881
Increment	0	25	75
Mexico:			
Baseline scenario	23397	22927	22586
Mitigation scenario	23397	23520	24376
Increment	0	593	1790
Tanzania:			
Baseline scenario	128	128	128
Mitigation scenario	128	181	332
Increment	0	53	204
Total			
Baseline scenario	58951	57444	56700
Mitigation scenario	58951	59208	62451
Increment		1764	5751
Increment (Including Brazil)		1851	6199

Notes: Increment (T) = Mitigation (T) – Baseline (T)

Brazil – Baseline carbon stock was not estimated. Incremental carbon stock created in short- and long-rotation plantations by 2012 is 87×10^6 Mg C and by 2030 it is 448×10^6 Mg C.

the primary contributors, in Mexico restoration plantations and managed forests are the largest contributors, and in Tanzania community plantations form the most significant mitigation option.

The cumulative potential for the seven study countries increases to 6199×10^6 Mg C by 2030. Mexico, Indonesia, Brazil and India, four of the larger forested countries in the study group, offer significant potential for carbon capture by this period. The potential is limited in the Philippines due to its relatively small land area. On an annual average basis, the potential for the seven countries amounts to about 140×10^6 Mg C yr^{-1} between 2000 and 2012, and 230×10^6 Mg C yr^{-1} between 2012 and 2030.

This study estimates the cumulative potential in Brazil for short- and long-rotation plantations to be 87×10^6 Mg C by 2012 increasing to 448×10^6 Mg C by 2030, but it did not evaluate the potential for avoidance of emissions from deforestation. A recent report (Da Motta et al. 1999) suggests that this potential is of the order of 2718×10^6 Mg C, and that for natural forest management amounts to another 735×10^6 Mg C. Combined with the estimate in this study, the total cumulative potential in Brazil for the four options is about 3900×10^6 Mg C, or almost 68% of the cumulative amount estimated for all other study countries together by 2030.

As noted in Section 4 below, only some of this potential is estimated to be such that its direct benefits exceed direct costs. Additional carbon can be sequestered at a net cost to the economy. Many barriers that are explained in Section 4.5, however, limit the potential that may be realized.

4. Economic Implications of the Carbon Scenarios

The activities noted in Table I form the basis for the mitigation carbon scenarios shown in Table V. The initial cost, rotation period, and mean annual increment ranges for each activity are shown in Table II. In this section, we focus on two topics, (1) cost-effectiveness of mitigation options and the potential for carbon sequestration and emissions avoidance (Section 4.1), and (2) present value of the cumulative costs of mitigation scenarios (Section 4.2). The latter information is useful for potential investors and government policy makers in assessing the investment needed for a regional or national scenario that contains a mix of mitigation options.

Much of the economic analysis of climate change mitigation options in the forestry and other sectors has focused on the estimation of the cost effectiveness (costs or net benefits per Mg C) of options (Brown et al. 1996; Kauppi and Sedjo 2001). Such estimates permit a ranking of options by their costs or net benefits, and constitute useful information for policy makers about the comparative importance of each option.

4.1. Cost Effectiveness of Mitigation Options

The cost effectiveness of mitigation options, i.e., an option's *cost per Mg C,* depends on the extent to which all factors contributing to net costs and changes in carbon stock have been included, and the time period over which these are measured. The reporting of costs of LULUCF mitigation options has largely been limited to the estimation of investment or establishment cost per ha or per Mg C (Brown et al. 1996, 2001). Kauppi et al. (2001) provide additional information on the net present value (NPV) per Mg C for selected forestry options in developing countries. The F7 group of experts published an estimate of the establishment cost and NPV per Mg C for Brazil, India, China, Malaysia, Mexico, Tanzania, and Thailand in 1995 (Sathaye and Makundi 1995). The data and information reported in this set of studies expands that approach to the estimation of costs by reporting the annualized cost per Mg C for a specified period, and the mitigation carbon potential relative to a baseline scenario. Further, these estimates report costs that are incremental to the costs of an alternate baseline for each option.

For estimating cost effectiveness of options our approach is to account for all the dominant costs and non-C benefits of an option, annualize these for a specified period (2000–2030), and then express the net costs in terms of the average annual C emissions avoided or carbon sequestered, i.e., the annualized net cost (benefit) per Mg C (henceforth referred to as cost per Mg C). We report this parameter for the mitigation option after deducting the cost per Mg C estimated for a baseline alternate for each option. The baseline alternate may be viewed as representing the foregone opportunity cost of the option. This approach to estimating cost of mitigation options is similar to that described by UNEP for energy projects (UNEP 1998). The estimated value may be compared with a potential international price of carbon, or the cost per Mg C for energy projects.

An important caveat is worth noting in using this approach. Carbon flows of forestry projects unlike those from energy projects vary over time. An energy mitigation project is assumed to provide constant annual emissions reductions, but the amount of C sequestered in a forestry project varies annually and reaches equilibrium after a species reaches maturity or is sustainably harvested. The cost per Mg C for forestry options is thus sensitive to the time horizon under consideration. Averaging annual C flows over a defined time period is thus only useful as an artifact that permits the cost per Mg C for forestry options to be compared with that for energy options.

The cost per Mg C was estimated for each study country for the options listed in Table I. The cost per Mg C was matched with the cumulative vegetation carbon sequestered or emissions avoided between 2000 and 2030 and is shown in Figures 1 to 7 for the study countries, and for all countries combined in Figure 8.

A discount rate of 10% real (after accounting for inflation) is used for China, Indonesia, Mexico, Tanzania and Brazil, and 12% real for India and the Philippines. These rates reflect the rates used by multilateral banks to evaluate energy

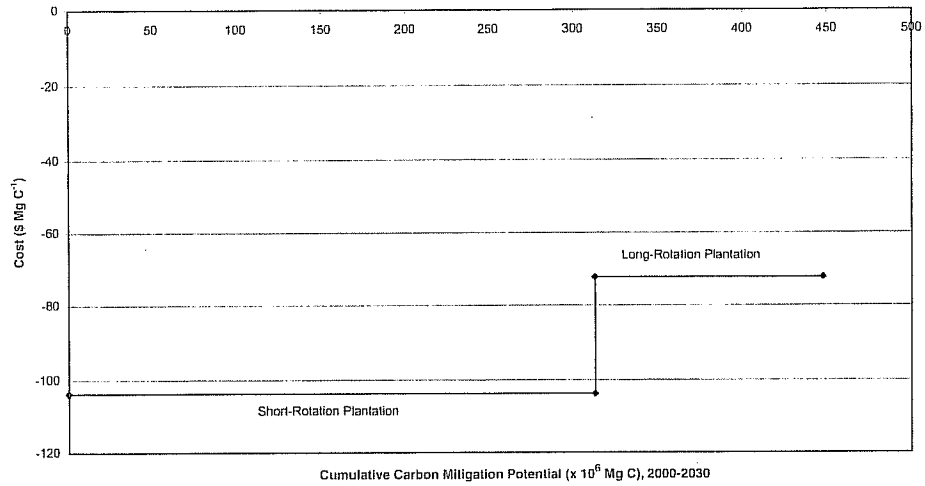

Figure 1. Forestry mitigation potential, Brazil (Short- and long-rotation plantations).

and forestry projects in the study countries. Private discount rates are likely to be much higher, e.g., approaching 18% real in Brazil (Meyers et al. 2001). On the other hand, the Indian Planning Commission has suggested a rate of 6% for environmental projects (Kadekodi and Ravindranath 1998).

For each country, the cost curve begins with a negative cost per Mg C. A negative cost indicates that the direct revenue generated by the mitigation option from the sale of timber and other products exceeds its costs, including the opportunity costs. The carbon potential at a negative cost per Mg C varies across countries. This potential depends on the options selected for study in each country, the magnitude and time profile of the baseline and mitigation carbon, its costs, and the prices and yields of timber and non-timber products. The time profile of the above monetary and C factors has a significant impact on the estimated costs because of the aforementioned high discount rates.

In China, because of the high price that timber and non-timber products are assumed to fetch relative to costs, all nine options (three different ones in each of the three study regions) are estimated to have a negative cost per Mg C, and for similar reasons, the costs are negative for Brazil. On the other hand for India, cost per Mg C is negative only for the regeneration option largely because its cost of planting is very small. Short-rotation plantations and regeneration offer negative cost opportunities in the Philippines. Short-rotations plantations also have negative costs in Mexico, Indonesia and Tanzania. In Mexico, long-rotation plantations, forest management and bioenergy are estimated to be negative cost options too. All other options are estimated to have positive costs. Due to the high opportunity cost of land, forest protection is the highest cost option in India, the Philippines and Indonesia, the three countries that evaluated this option.

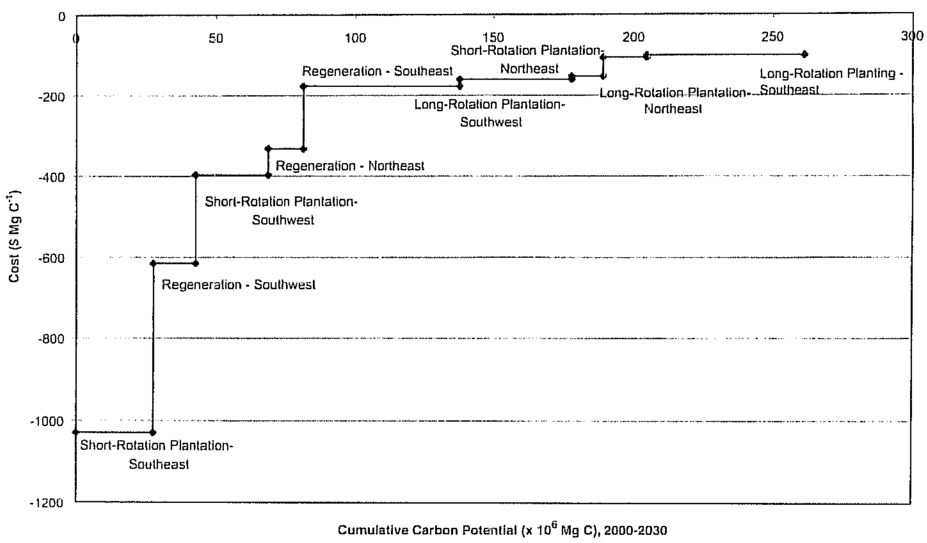

Figure 2. Forestry mitigation cost curve, China (Short- and long-rotation plantations, and regeneration options).

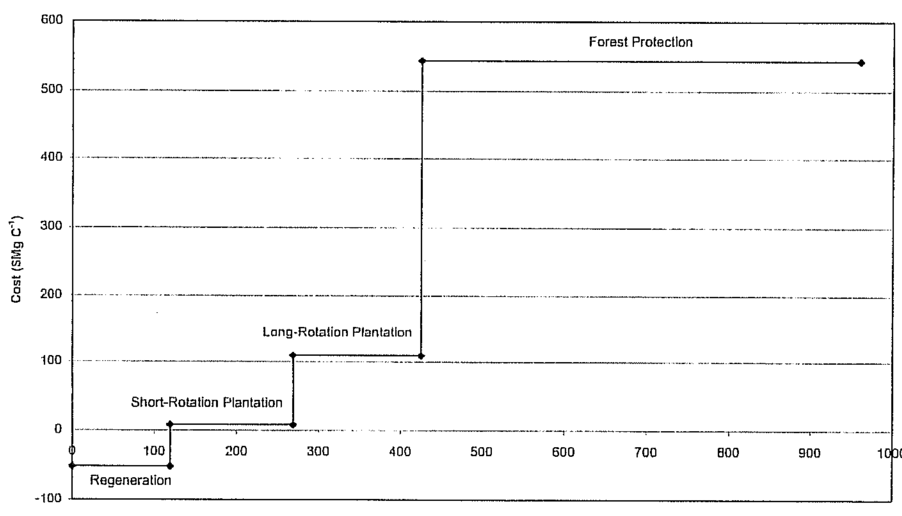

Figure 3. Forestry mitigation potential, India (Short- and long-rotation plantations, regeneration and protection).

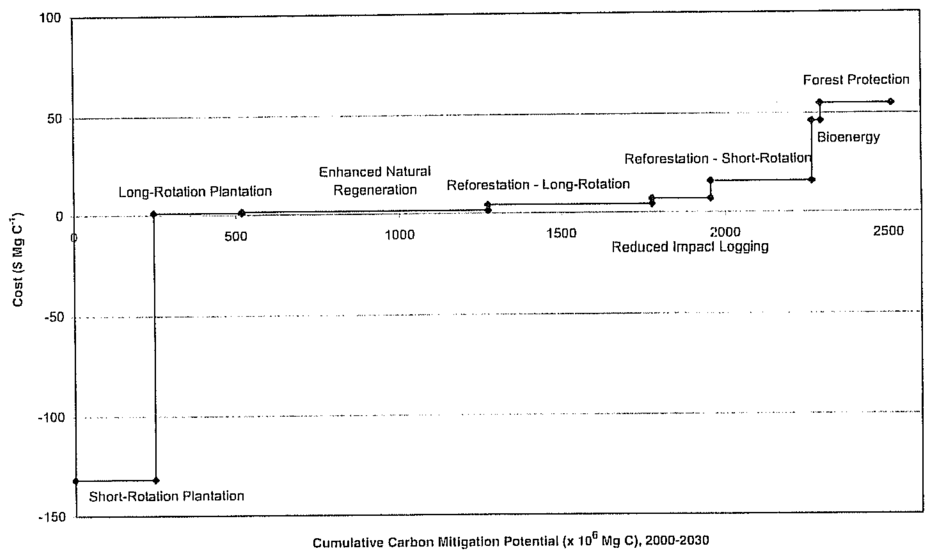

Figure 4. Forestry mitigation potential, Indonesia (Short- and long-rotation plantations, natural and enhanced regeneration, protection).

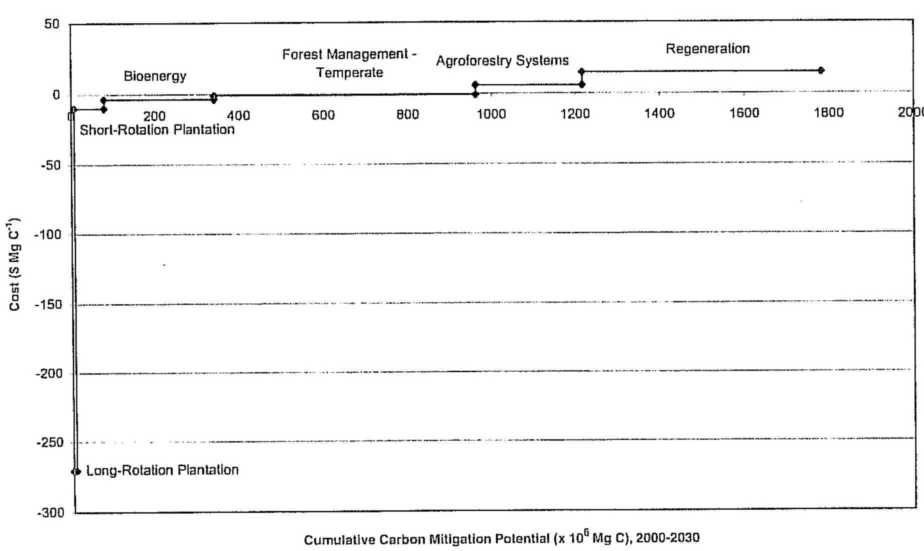

Figure 5. Forestry mitigation potential, Mexico (Short- and long-rotation plantations, regeneration, forest management, agroforestry).

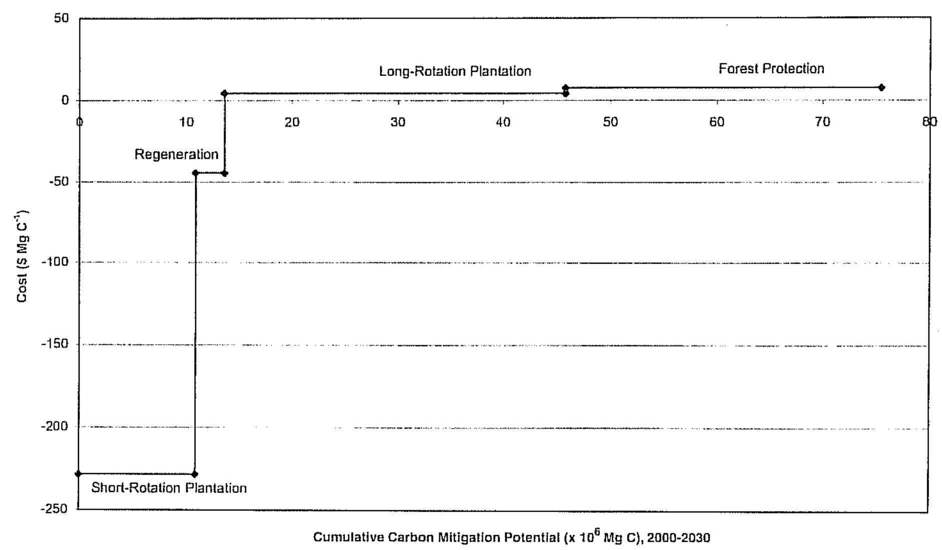

Figure 6. Forestry mitigation potential, Philippines (Short- and long-rotation plantations, regeneration and protection).

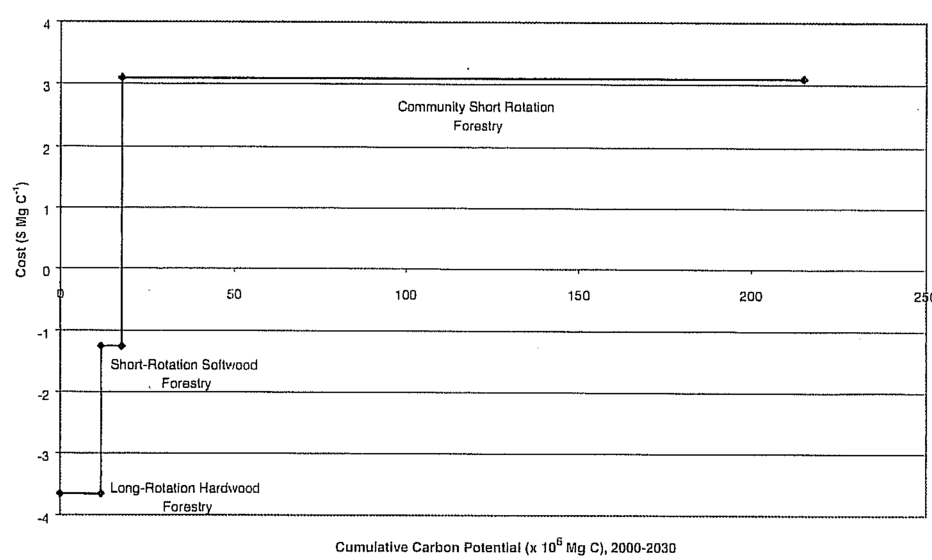

Figure 7. Forestry mitigation potential, Tanzania (Short- and long-rotation plantations).

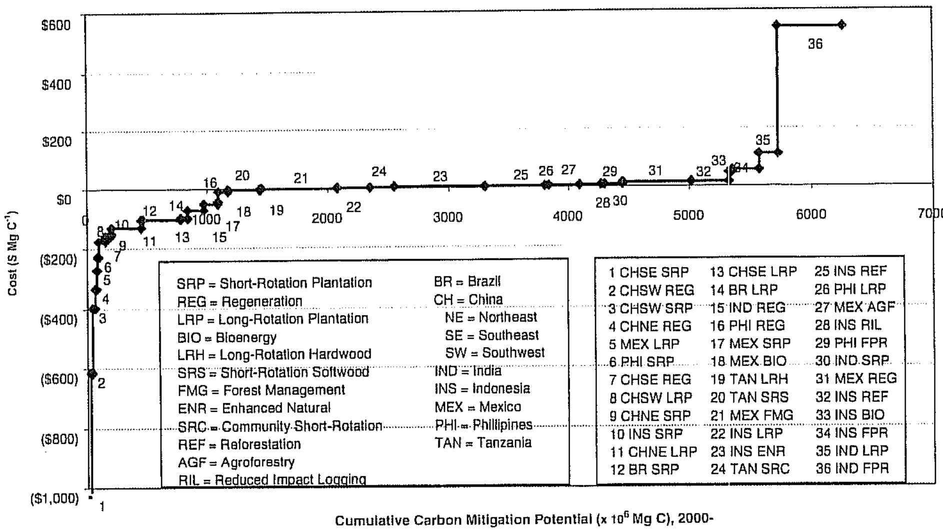

Figure 8. Forestry mitigation potential (Brazil, China, India, Indonesia, Mexico, Philippines and Tanzania).

The larger countries dominate the combined potential for C sequestration (Table V). The combined cost curve for all options across the study countries shows that about half the cumulative C potential may be realized at negative cost (Figure 8). Coincidentally, this finding is similar to that reported for the energy sector by the IPCC (Moomaw and Moreira 2001). The IPCC reports that about half the technology potential worldwide could be tapped at a negative cost and the other half at a cost ranging up to $100 per Mg C.

The positive cost potential may be compared with the carbon price that would be needed to implement these options. Under a C price of say $20 per Mg C, the cumulative potential between 2000 and 2030 amounts to 5 Pg C (Figure 8).

The cost curve in Figure 8 does not take into consideration barriers that would increase the cost and reduce the potential as indicated in Figure 9, and discussed in Section 4.5 below.

4.2. Costs for a Mitigation Scenario

Table VI shows the discounted present value of the cumulative cost of the mitigation options assessed for the period 2000 to 2012 and 2000 to 2030. Figures in these two columns provide information regarding the estimated cost to implement a mitigation scenario without regard to its monetary benefits, i.e., the revenue generated from the sale of timber and non-timber products, and carbon, and baseline conditions. The cumulative cost in 2000–2030 is almost double that in the earlier period.

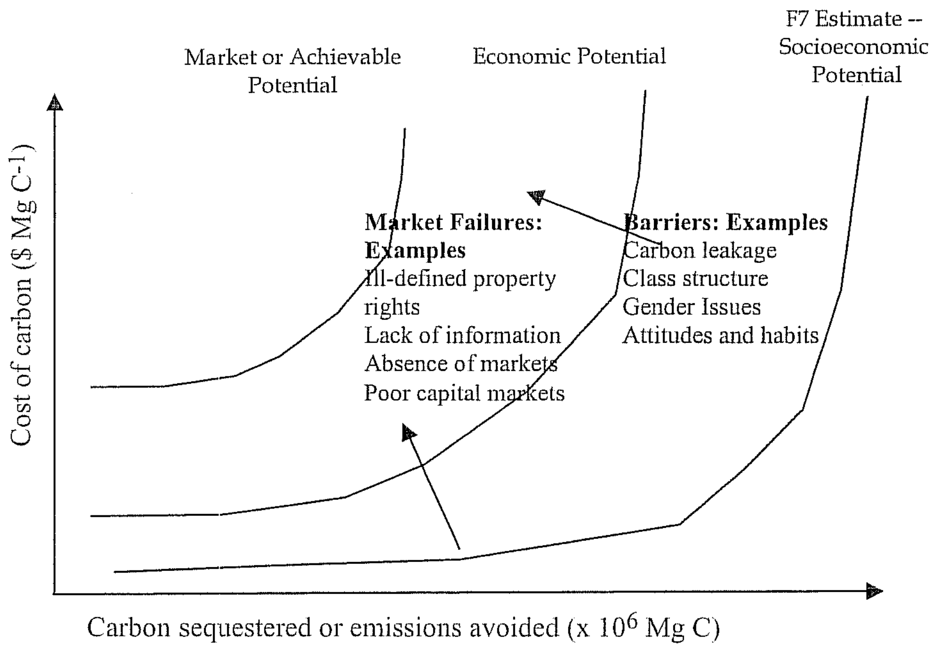

Figure 9. Conceptual impact of barriers on costs and C potential. Carbon mitigation potential and costs estimated in this paper refer to the socioeconomic potential. Barriers and market failure can reduce the potential to the economic and market potential and increase costs. (See Sathaye and Bouille (2001) for a definition and description of these concepts).

TABLE VI

Present value of costs for mitigation scenarios (US \$ $\times$ 10^6 1998) in seven countries

Country	2000–2012	2000–2030
Brazil	590	1,206
China	589	1,390
India	615	1,194
Indonesia	4,950	8,601
Philippines	82	151
Tanzania	49	165
Total	6,875	12,707

Note: Costs reflect only the assessed options. For Brazil, only forestation options are evaluated. For India, cost of forest protection is not included.

TABLE VII

Incremental carbon stock projected for the tropics for the study options

	2000–2012		2000–2030	
	Cumulative ($\times 10^6$ Mg C)	Annual average ($\times 10^6$ Mg C yr^{-1})	Cumulative ($\times 10^6$ Mg C)	Annual average ($\times 10^6$ Mg C yr^{-1})
F7 Countries	1,851	140	6199	200
All-Tropics	2,730	210	9,028	290

Note: Annual average figures are based on simple averaging over the respective periods. Actual stock change profile over each period depends on the mean annual increment, rotation period, and magnitude of land-use change for each analyzed option. Annual average values may not be representative of stock change for any given year.

The cost figures include the opportunity cost of land for the forest protection option. Other costs of alternate baseline options are not deducted. These projected costs may be compared with historical data on the funds allocated from the government budget to the forestry sector in each country. The government budget varies in each country, but in all cases it represents a fraction of the cost reported in Table VI for a carbon mitigation scenario.

4.3. ALL TROPICS C POTENTIAL FOR OPTIONS ASSESSED IN STUDY COUNTRIES

We estimated the C mitigation potential for all tropics, for the F7 study options, by extrapolating the estimates for the F7 study countries. The F7 mitigation potential was scaled up through the extrapolation of current trends in land area and product quantity for tropical Africa, Asia and Latin America. The results from this simple extrapolation are reported in Table VII.

For tropical Asia, the short and long rotation forestry options in the Asian F7 countries (China, India, Indonesia and the Philippines) are estimated to represent 70%, and enhanced natural regeneration 80%, of the potential in the region. Reduced impact logging and bioenergy options in the Asian F7 countries represent about 30% of the potential in tropical Asia.

For Latin America, long-rotation options in Mexico and Brazil were estimated to represent 70% of the regional potential, while short rotation and bio-energy options the coverage was estimated to be 60%. Forest management represented 70% and agroforestry was estimated at 50% of the regional potential.

For tropical Africa, the options considered in Tanzania are estimated to cover from 25% to 40% of the potential, though many other potential options such as conservation were not analyzed in this study.

The extrapolation to the Latin American and African tropics may underestimate the potential in these regions due to underrepresentation of the options analyzed in the F7 countries, as well as the limited mitigation activities that were analyzed in the represented countries. For example, the potential for avoiding deforestation in the Amazon region could be much larger and may not be fully accounted by the estimated 20% used in this study. Table VII shows the potential in the F7 countries, and the estimated mitigation potential for the tropics. The F7 study countries account for about two-thirds of the mitigation C potential in the tropics for the analyzed options.

4.4. Applicability of the Approach to Carbon Mitigation Projects

The estimation of mitigation costs and C potential was done at the *activity level* for each study country. It is instructive to evaluate the consistency of the above estimation approach with a *project-level* one. Climate mitigation projects will have to address several key issues, such as baselines, environmental additionality, permanence and leakage of carbon stocks, and the monitoring and verification of carbon benefits. The mitigation potential estimated above is incremental to a biomass baseline at the site level, and also to a biomass baseline scenario of land-use changes. At the site level, the assessment subtracts the change in C stock and net cost per ha that might have occurred had the activity not taken place. At the scenario level, the mitigation potential reflects the increase in C stock incremental to a baseline scenario of land-use change.

The additionality of the estimated potential will depend on the price of C. Potential estimated above the C price is clearly additional to that which would have happened otherwise. The remaining potential is below the price of C, and some of it has a negative cost, which implies that many barriers prevent its realization. This potential may be deemed additional since it requires the removal of barriers that are discussed in the following section.

The above analysis focuses on the change in C stock over a limited period, from 2000 to 2030. It thus assumes that C stock is not lost during this period. Subsequent loss of C is not explicitly addressed in the assessment but would be of concern to project developers who may incur liability if the C stock is disturbed. Similarly, physical or market leakage of the C stock would reduce the estimated carbon potential. The leakage issue is not addressed in the above assessment (see Brown et al. 2000; for additional discussion of permanence and leakage of C from projects).

Monitoring costs are included in the cost estimates for each option. The incremental cost for measuring or estimating carbon are not expected to be large for forestation options, since normal monitoring would include items that form the basis for estimation of C stock, such as an assessment of vegetation growth and soil minerals.

4.5. Limitations of the Analysis

Our estimates serve as an upper bound on the potential for selected types of forestry projects that could be pursued under international agreements or programs that allow GHG emissions offset activities overseas. The realizable potential, however, is likely to be less than that estimated here. Typical barriers – institutional inertia, unclear land tenure, rights of indigenous populations, stringency of GHG accounting and other criteria for project acceptance, etc., to the implementation of projects will limit the estimated potential (Sathaye and Bouille 2001) as illustrated conceptually in Figure 9. The lack of in-country and international capacity to formulate, implement, and monitor climate change forestry projects will add to these barriers. The F7 study estimates represent what is labeled as the socioeconomic potential. This was estimated as the cost effective potential without regard to the various barriers that might preclude its achievement. Market barriers such as gender issues, attitudes, habits, cultural practices, etc. may limit the adoption of these options and reduce the potential to what is referred to as the economic potential. Additional barriers, often referred to as market failures by economists, may further constrain the potential to the achievable or market potential. Once the transaction costs of project implementation are added to the above estimates, the costs per Mg C will be higher than those estimated above.

The use of typically higher private instead of social discount rates will capture some of the aforementioned issues and yield a higher cost for each option. But the discount rate is a blunt instrument, and will not provide insights into the types of measures that might be appropriate to overcome each barrier, and the extent to which a combination of barriers will reduce the carbon potential of each option.

We report on the combined costs per Mg C for all options across countries in Figure 8, but because we have not included a shadow price for the exchange rate, capital, labor and other parameters, the reported estimates may not be strictly comparable across countries.

The above analysis assumes that land area will be converted in a uniform manner beginning in 2000. In practice, without the presence of institutions to establish projects, and government procedures for the approval and acceptance of their claims to carbon, projects will ramp up over a period of years. This ramp up will limit the amount of C that might be available for international trading particularly during the 2000–2010 period.

5. Summary

This paper summarizes the studies of potential for carbon sequestration and emissions reduction in the forestry sector in seven developing countries that account for about 60% of the forested area in the developing world. The estimated cumulative potential amounts to 1851×10^6 Mg C by 2012 and 6199×10^6 Mg C by 2030, and the average annual to about 140×10^6 Mg C yr^{-1} between 2000 and 2012, and 230×10^6 Mg C yr^{-1} between 2012 and 2030. This potential may increase if additional mitigation activities are evaluated, especially those that avoid deforestation in Brazil.

The studies report on the costs and benefits of LULUCF carbon mitigation options in the study countries. The results show that about half the mitigation potential of 6.2 Pg C between 2000 and 2030 in the seven countries could be achieved at a negative cost, about 5 Pg C at a cost less than $20 per Mg C, and much of the rest at costs ranging up to $100 per Mg C. Negative cost potential indicates that non-carbon revenue is sufficient to offset direct costs of these options.

The cost of carbon (annualized net cost per Mg C) for the evaluated options varies across countries. It is negative for the forestation options for China, Mexico and Brazil, the regeneration option in India and the Philippines, the bioenergy option in Philippines and Mexico, and short rotation community forestry in Tanzania. The cost is positive and highest for all forest protection options primarily due to their high opportunity costs, which are only partially offset by the benefits of forest protection.

The magnitude of the cost-effective potential for carbon forestry projects estimated in these studies provides an upper bound on the realizable potential for the options selected for study in this group of countries. This potential is likely to be limited by the many barriers to project implementation in the study countries. These include the lack of access to credit, long gestation period for realizing timber revenue, lack of land tenure or ill-defined property rights, and the lack of infrastructure, institutions and markets. Estimates are needed of how these barriers might restrict the mitigation potential for LULUCF in specific countries, their impact on the costs of different options, and the implementation capacity requirements in the study countries.

Viable, analytically credible, carbon forestry projects could be designed to help local stakeholders increase their access to credit and to potentially provide carbon revenue in the early years of a project prior to timber-harvest or other revenues. Such projects could help reduce two key financial barriers to carbon mitigation projects, but other barriers would remain, and may require interventions by local, national or other governments, non-governmental organizations, and/or the private sector.

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Notes

1. We report the potential for C mitigation from a variety of forestry options. Some of the options are such that their non-carbon revenues exceed direct costs. Markets, institutional and socio-cultural barriers (Sathaye and Bouille 2001) to extensive expansion of these options as projected in these studies, however, were not considered in the evaluation of the potential and costs. These may prevent or delay the implementation of the options, and reduce their estimated potential and increase costs.
2. The IPCC reports an estimated 1146 Pg C stored within the 4.17 billion hectares of tropical, temperate and boreal forest areas, a third of which is stored in forest vegetation (IPCC 2000). Another 634 Pg C is stored in tropical savannas and temperate grasslands.
3. Carbon emissions from land-use change worldwide during 1989–98, for instance, are estimated to be 1.7 ± 0.8 Pg C yr^{-1} (Watson et al. 2000). This is offset by terrestrial uptake of CO_2 and results in a net terrestrial uptake of 0.2 ± 1.0 Pg C yr^{-1}.
4. For example, examination of data from Tanzania where the currency was systematically devalued thirty-fold between 1986 and 2000, (from 27 to 800 Shillings/ US dollar), shows the establishment cost for a forest plantation in the same locality (Sao Hill) changed from US \$217 to US \$200 ha^{-1} (Makundi 2001). The prices of forest products show similar stability over the period. This would tend to support the use of a pre-devaluation cost structure, since the current costs and prices are transitional and may be more reflective of the short-term shock associated with massive currency devaluation, than the underlying cost structure of a plantation program which is a long term activity.
5. The COMAP model version 3 computes the equilibrium carbon stock in live and decomposing vegetation, soils and products. It also computes the annual live vegetation carbon stock from 1990 to 2030. We report on the changes in the annual vegetation stock in this section.

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